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A regional paleomagnetic study of lithotectonic domains in the Central Gneiss Belt, Grenville Province, Ontario

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Abstract

We have made a regional paleomagnetic study of lithotectonic domains in the Central Gneiss Belt of the Grenville Province in Ontario along ten N–S and E–W traverses up to 200 km in length. Although originally intended to clarify the tectonic mechanism by which these exotic terranes were assembled and welded to the Archean Superior craton during the ~1150-Ma Grenvillian orogeny, we actually learned much more about the timing of post-orogenic uplift of the various domains around 1000–900 Ma as they stabilized and became part of the Rodinia supercontinent. The normal (N) and reverse (R) natural remanent magnetizations (NRMs) of all domains, as well as those of reactivated regions flanking the Grenville Front (GF, the Superior–Grenville boundary) to the north and south, have paleomagnetic poles falling on the 980–920-Ma (^{40}Ar/^{39}Ar calibrated) portion of the Grenville apparent polar wander track for Laurentia. There is a general tendency for paleopoles to young with increasing distance of domains from the GF, implying that more southerly domains were uplifted and magnetized later, but two of the domains do not fit this pattern. Previously reported younging trends away from the GF, based on K/Ar thermochron maps and paleomagnetic 'zone poles', are untrustworthy because of hydrothermal alteration, which causes chemical remagnetization and anomalously old K/Ar ages near the GF. Another trend in our data is a regular increase in the R/N ratio with increasing distance south of the GF. In the reactivated zones flanking the GF, NRMs are overwhelmingly of N polarity, whereas well away from the GF, R/N is close to 50 : 50. Also, NRM intensities and susceptibility values increase 100-fold away from the GF, peaking ≈10 km south of the front, with a pulse-like pattern similar to that documented in anomalously high ^{40}Ar/^{39}Ar dates in the same region. Both the magnetic and Ar/Ar results are likely due to a 'wave' of hydrothermal alteration and remagnetization during which fluids were driven away from the GF. Since the remagnetized NRM near the GF has approximately the same direction as NRMs in domains away from the GF, hydrothermal activity along fault systems south of the GF must have continued until ~1000 Ma, long after the collisional orogeny itself. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: paleomagnetism; tectonics; Central Gneiss Belt; natural remanent magnetization

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1. Introduction

The Central Gneiss Belt (CGB) of the Precambrian Grenville Province in Ontario (Fig. 1) is a high-grade metamorphic terrain comprising 14 allochthonous lithotectonic domains and subdomains and an autochthonous region of reactivated cratonic rocks, the Grenville Front Tectonic Zone (GFTZ), bounded by the Grenville Front (GF) to the north [1]. Our regional paleomagnetic study covers all these domains and zones. Based on a report of primary natural remanent magnetization (NRM) in the French River area [2], just south of the GFTZ, we had hoped to recover possibly three generations of NRMs: (1) pre-orogenic NRMs acquired before the Grenvillian orogeny; (2) synorogenic NRM overprints dating from collision and suturing of the Southern/Superior craton with the Grenville exotic terranes, now pre-

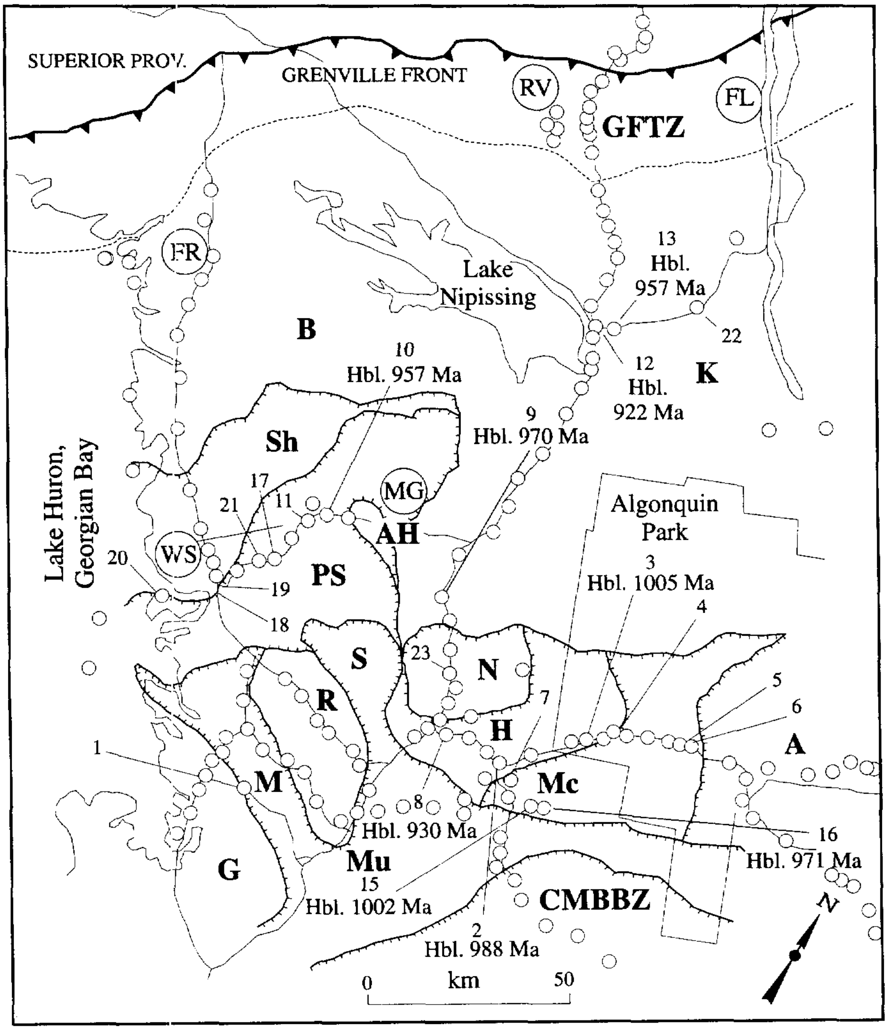

Fig. 1. Map of the Muskoka–Parry Sound–Nipissing region of the Grenville Province in Ontario, showing our sampling sites in the Grenville Front Tectonic Zone (GFTZ) and in the lithotectonic domains and subdomains of the Central Gneiss Belt: *B* = Britt; *Sh* = Shawanaga; *K* = Kiosk; *PS* = Parry Sound; *Ah* = Ahmic; *PS* = Parry Sound; *N* = Novar; *A* = Algonquin; *H* = Huntsville; *Mc* = McLintock; *R* = Rosseau; *S* = Seguin; *Mu* = Muskoka; *M* = Moon River; *G* = Go Home; *CMBBZ* = Central Metasedimentary Belt Boundary Zone. The overthrust side of boundaries is indicated by ticks or teeth. Previous paleomagnetic studies, *RV*, *FL*, *FR* and *WS* are described in the text. Sites numbered *1–23* were sampled previously by Cosca et al. [32]; their $^{40}Ar/^{39}Ar$ hornblende dates are indicated.

served as CGB domains; and (3) post-orogenic NRM overprints dating from uplift and cooling of these domains. NRMs of the first two types would give information about structural rotations during thrusting, differential burial depths and times for various subdomains, and the amount of overthrusting and differential burial across the GF.

However, the high temperatures reached during metamorphism in the CGB have obliterated pre-orogenic and synorogenic magnetizations. All NRMs recovered in our study resemble post-tectonic uplift remagnetizations documented in paleomagnetic studies in the Central Metasedimentary Belt (CMB) to the southeast (e.g. Refs. [3–5]). There is thus no direct paleomagnetic indication of the pre-collisional positions of Grenvillian terranes or their vertical, horizontal, and rotational movements during suturing, except that found in a previous study in the CMB [6]. Our main objective, once it became clear that synorogenic and pre-orogenic NRMs were not preserved in the CGB, was to see if uplift NRMs are present quite generally across the region northwest of the CMB and south of the GF, and what cooling history they reveal.

2. Geological and tectonic setting

Across the Grenville Front (GF), a major southeast dipping structural boundary [7], the metamorphic grade changes from generally greenschist grade in the Southern and Superior Provinces to the northwest to amphibolite or granulite grade in the CGB [8]. The CGB is separated from the less metamorphosed CMB to the southeast by the Central Metasedimentary Belt Boundary Zone (CMBBZ), a broad, southeast dipping ductile shear zone [9].

The domains and subdomains of the CGB are separated by shear zones recording generally northwest directed low-angle thrusting [8,10,11]. Lithologies are varied, with quartzofeldspathic gneisses and amphibolites of igneous origin dominating [8]. Nd model crustal formation ages for gneisses are 1900–1800 Ma in the Britt, Kiosk, Rosseau, and Go Home domains, ≈1750 Ma in the Novar, Huntsville, and McLintock subdomains, and 1550–1350 Ma in the Parry Sound and Muskoka domains, including Moon River and Seguin subdomains [12].

Each subdomain is believed to have originated as a deeply buried crustal slice that was overthrust northwestward along low-angle, imbricate ductile shear zones and later exhumed by erosional unroofing and uplift [8]. These terranes were stacked and welded to the Superior craton, and to the Rodinia supercontinent (e.g. Refs. [13,14]), in the Grenvillian Orogeny, between ≈1160 and 1100 Ma (U/Pb zircon dates from pegmatites in the Parry Sound, Moon River and Seguin boundary shear zones [15,16]). Metamorphic mineral assemblages record temperatures, pressures, and inferred equilibration depths during metamorphism of 650–800°C, 8–11 kb, and 30–40 km, respectively [17].

The GFTZ has a different history. Partial lead loss from primary zircons and growth of new zircons is recorded at numerous locations from Georgian Bay to Labrador between 996 and 975 Ma [18, 19]. Titanite ages from the same late melts are analytically identical to zircon growth ages. Thus post-metamorphic uplift and cooling must have been rapid, in contrast to the slow uplift and cooling inferred for the CMB and CGB from ^{40}Ar/^{39}Ar thermochronometric studies [20,21].

3. Paleomagnetic background

The spatial pattern and typical unblocking temperatures of Grenvillian overprints of NRM have been investigated for rocks just north of the GF [22,23]. Post-Grenvillian uplift and cooling occurred ≈1000–900 Ma ago and peak temperatures $\leq$400°C were reached 2 km north of the GF [23]. There has been no corresponding investigation of NRM directions and unblocking temperatures of the more deeply buried rocks just south of the GF, apart from early studies of the River Valley and Fall Lake anorthosites ([24]; RV, FL in Fig. 1) and a more detailed study in the French River area ([2]; FR). In the CGB proper, there have been only two previous paleomagnetic studies, both in the Parry Sound domain, of the Whitestone anorthosite [25] and the Magnetawan metasediments [26] (WS and MG in Fig. 1). The present study greatly increases the paleomagnetic database for the CGB and the adjacent GFTZ.

Post-tectonic secondary uplift magnetizations constrain the timing of unroofing and cooling, and via the characteristic NRM unblocking temperatures, the maximum depth of burial. When combined with $^{40}Ar/^{39}Ar$ mineral ages and closure temperatures, uplift overprints can document the cooling history of parts of an orogen. In the Hastings area of the CMB, immediately southeast of the CMBBZ, $^{40}Ar/^{39}Ar$ thermochronometry [20] has shown that cooling from ≈600 to ≈350°C required 160 Ma, from 980 to 820 Ma. This work not only demonstrates that post-tectonic uplift and cooling were very slow, but also provides dated reference paleopoles that anchor the Grenville apparent polar wander path (APWP).

McWilliams and Dunlop [27] pointed out that Grenville paleomagnetic zone poles trace out a simple path when plotted in order of increasing distance from the GF. There is a parallel pattern of younging in K/Ar and other radiometric dates away from the GF [28–31]. These patterns suggest that either different regions were uplifted from different original depths, or else the geothermal gradient was greatly enhanced over relatively short horizontal distances. Our study tests the existence of a similar pattern in CGB paleomagnetic results.

4. Sampling scheme and measurements

We sampled 154 sites (8–10 samples per site) in 10 traverses of regional extent, mainly along highways and the Georgian Bay coastline, extending ≈200 km south from the Grenville Front to the southern limit of Precambrian exposure in the Go Home domain (Fig. 1). The lithotectonic regions and domains sampled in reasonable detail (≥10 sites) are: north of the GF (reactivated zone); GFTZ; Kiosk (K); Britt, including the Britt (B) and Shawanaga (Sh) subdomains; Parry Sound (PS); Algonquin, including Algonquin (A), Novar (N), Huntsville (H) and McLintock (Mc) subdomains; Muskoka, including the Muskoka (Mu), Seguin (S) and Moon River (M) subdomains; Rosseau (R); and Go Home (G).

We planned our sampling to take advantage of existing $^{40}Ar/^{39}Ar$ dates in the CGB [32–34], particularly for hornblende because of the close match between its closure temperature and typical magnetite NRM unblocking temperatures (500–600°C). Numbered sites in Fig. 1 are those of Cosca et al. [32]; their hornblende dates are noted on the map. Sites in the Georgian Bay area made use of hornblende $^{40}Ar/^{39}Ar$ dates by Culshaw et al. [33]. About half our sites north of the GF and in the GFTZ were sampled and $^{40}Ar/^{39}Ar$ dated by Smith et al. [34].

Our goal was to sample the CGB subdomains as uniformly as possible. We therefore could not concentrate on the most favourable lithologies as in a conventional paleomagnetic study, in which one or a few formations are studied exhaustively and their results are taken to be representative of an entire region. In Precambrian metamorphic terrains, geological subdivisions based on lithologies and structures may not correspond precisely to regions of common uplift history, although our working hypothesis was that each subdomain was uplifted as a unit. Because our sites are separated by distances of 5–10 km, the usual averaging at sample, site and formation levels is changed to averaging at sample, site and subdomain levels. Subdomain averaging would not be justified for NRMs acquired before or during the Grenvillian orogeny, because different parts of the larger domains might have different structural corrections, but it is valid for post-tectonic NRMs acquired in passive uplift after thermal stabilization of individual domains.

Samples, oriented by magnetic and/or sun compasses, were sectioned into 2.2-cm-long specimens. One or two specimens of each sample were stepwise alternating field (AF) demagnetized in 5-mT increments up to 100 mT. Thermal demagnetization in steps to at least 600°C was carried out on fresh specimens of samples whose AF results were promising and also on some AF cleaned specimens whose NRM intensities remained high at 100 mT. Standard spinner magnetometers and demagnetizers were used.

5. Paleomagnetic directions and polarities

All stable paleomagnetic results were similar in direction to A magnetizations familiar from elsewhere in the Grenville Province and known to date from post-metamorphic uplift and cooling. Both reversed (R) and normal (N) polarities were found in most subdomains, often at the same site and sometimes superimposed in individual samples. (Because the forward connection between Grenvillian and Phanerozoic poles is not clear, absolute polarity is uncertain. We use the convention that positive inclinations correspond to N polarity.) Initially we will treat R and N results as independent magnetizations, A_R and A_N, for purposes of averaging but they are, in fact, almost antipodal and must be similar in age.

Fig. 2 plots site mean A_R and A_N results for the six domains or regions for which we have the most paleomagnetic data: north of the GF (including data from [23] as a single result); GFTZ (including RV + FL [24] as a single result); Britt (Britt and Shawanaga subdomains; FR [2] included as a single result); Kiosk; Algonquin (Algonquin, Novar, Huntsville and McLintock subdomains); and Muskoka. WS [25] and MG [26] were included with our data from Parry Sound (not illustrated). Each previous paleomagnetic study was treated as a single result because the geographic extent of each forma-

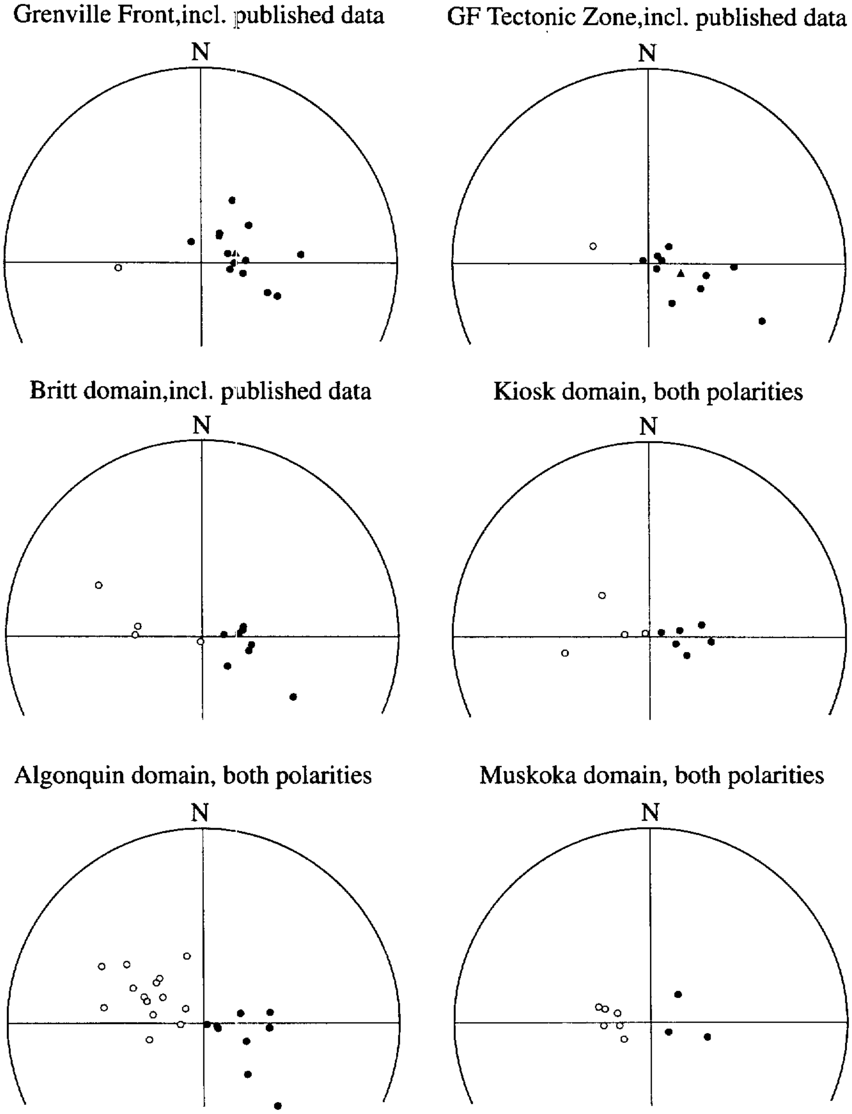

Fig. 2. Site mean paleomagnetic directions for reactivated zones north and south of the GF and for four major domains in the CGB. Open (closed) circles denote upward (downward) vectors. The reactivated zones near the GF have almost exclusively normal (N) polarity magnetizations, while more southerly domains have nearly equal numbers of N and reversed (R) results.

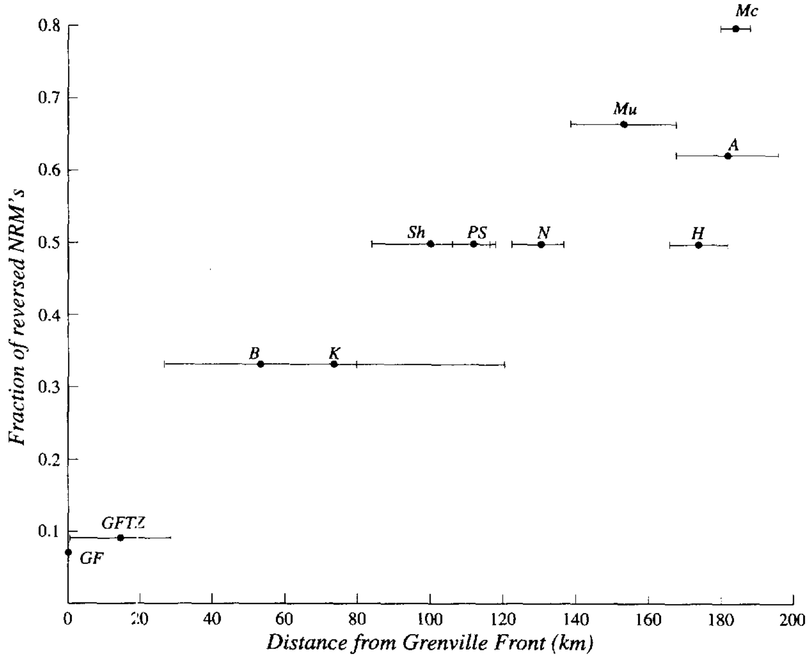

Fig. 3. The fraction of R polarity results as a function of distance from the GF. Error bars indicate the spread in distances for different sampling sites in a particular domain or region. The pattern seen in Fig. 2 is confirmed: the GF and GFTZ regions have almost no R polarity NRMs, while CGB subdomains beyond the reactivated zone have approximately 50 : 50 proportions of R/N results.

tion is comparable to the between-site spacing in our study. All regions and domains have quite similar westward and up (A_R) or eastward and down (A_N) NRMs. However, the proportion of R and N results is rather different for different domains, A_N being predominant close to the GF.

The apparent bias in NRM polarities depending on proximity to the GF is quantified in Fig. 3, where we plot the fraction of reversed results in each subdomain or region as a function of distance from the GF. NRMs from reactivated regions immediately north or south of the GF are overwhelmingly of N polarity, whereas NRMs from the Grenvillian terranes to the south have more or less equal proportions of N and R polarities. This general pattern could reflect relatively rapid acquisition of magnetization near the GF and slower cooling and NRM acquisition, spanning one or more field reversals, farther from the GF. Rapid cooling in the GFTZ and slow cooling elsewhere are also implied by U/Pb and ^{40}Ar/^{39}Ar dates, reviewed earlier. On a finer scale, there is a reasonable correlation between the fraction of R results in individual subdomains and distance from the GF.

6. Individual sample results

Figs. 4–6 give a few examples of AF and thermal demagnetization behavior of individual samples. Sample 523C-5 has three superimposed NRMs of similar magnitude, indicated by linear segments in the vector demagnetization trajectories (Fig. 4): a present earth's field overprint (0–4 mT), A_N (4–20 mT), and A_R (>20 mT). About half of A_R remains undemagnetized at 100 mT, but the shape of the AF decay curve, with a steady decrease over the 20–100 mT range, suggests fine-grained, nearly single-domain magnetite rather than hematite.

Samples 7-1 and 7-8 have dominant A_R NRMs with some superimposed A_N remanence (Fig. 5). A_N has coercivities up to 8 mT and unblocking temperatures below 360°C. A_R is almost exactly erased by AFs of 100 mT or heating to ≈560°C. It is carried entirely by low-Ti titanomagnetite (near-magnetite). The inflected form of the AF decay curve between 8 and 100 mT and the high average coercivities suggest a fine grain size (single-domain or pseudo-single-domain range: 0.1–10 μm).

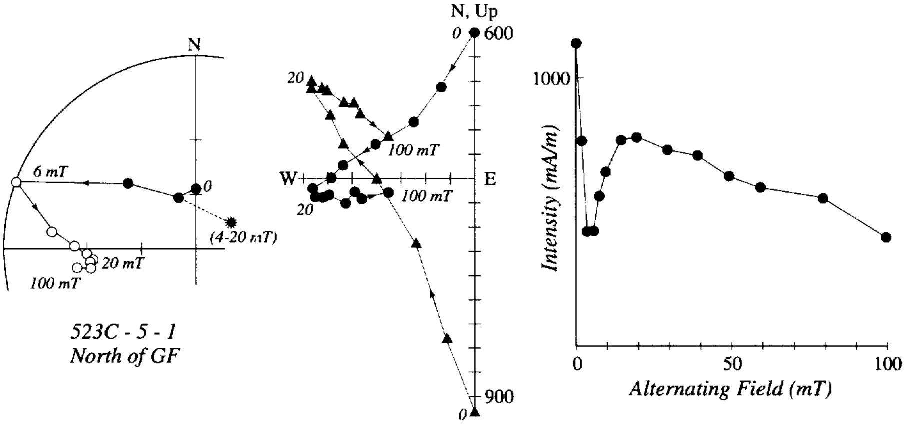

Fig. 4. Stereographic and orthogonal vector projections and total intensity variation of the magnetization of a sample from site 523 (north of GF) in the course of AF demagnetization. Circles and triangles are horizontal and vertical plane projections of the magnetization vector. The NRM of this sample has three superimposed vectors with non-overlapping coercivity ranges: present earth's field overprint (0–4 mT); N polarity A or A_N (4–20 mT); and R polarity A or A_R (20→100 mT).

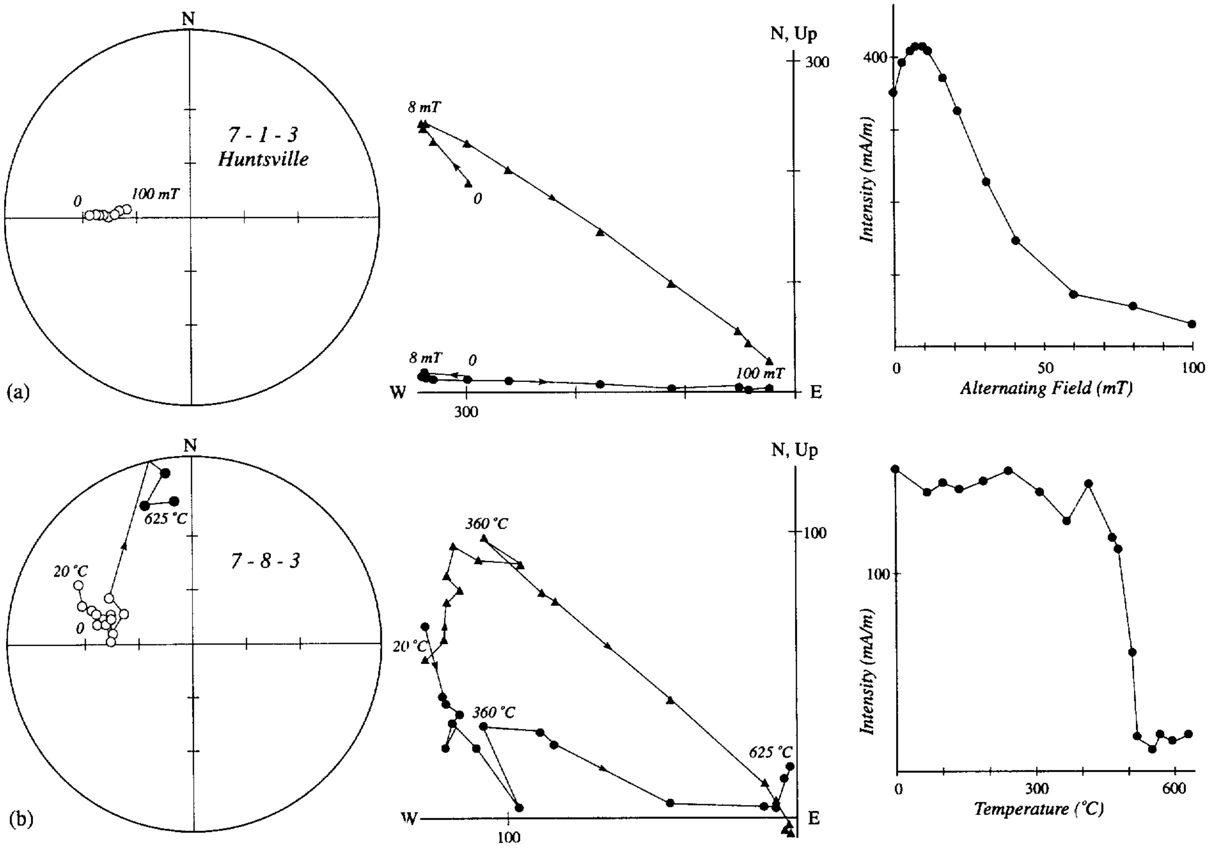

Fig. 5. AF and thermal demagnetization data for companion samples from site 7 (Huntsville subdomain). A_R, with 8–100 mT coercivities and 360–560°C unblocking temperatures, is dominant in these samples. Projections and symbols as in Fig. 4.

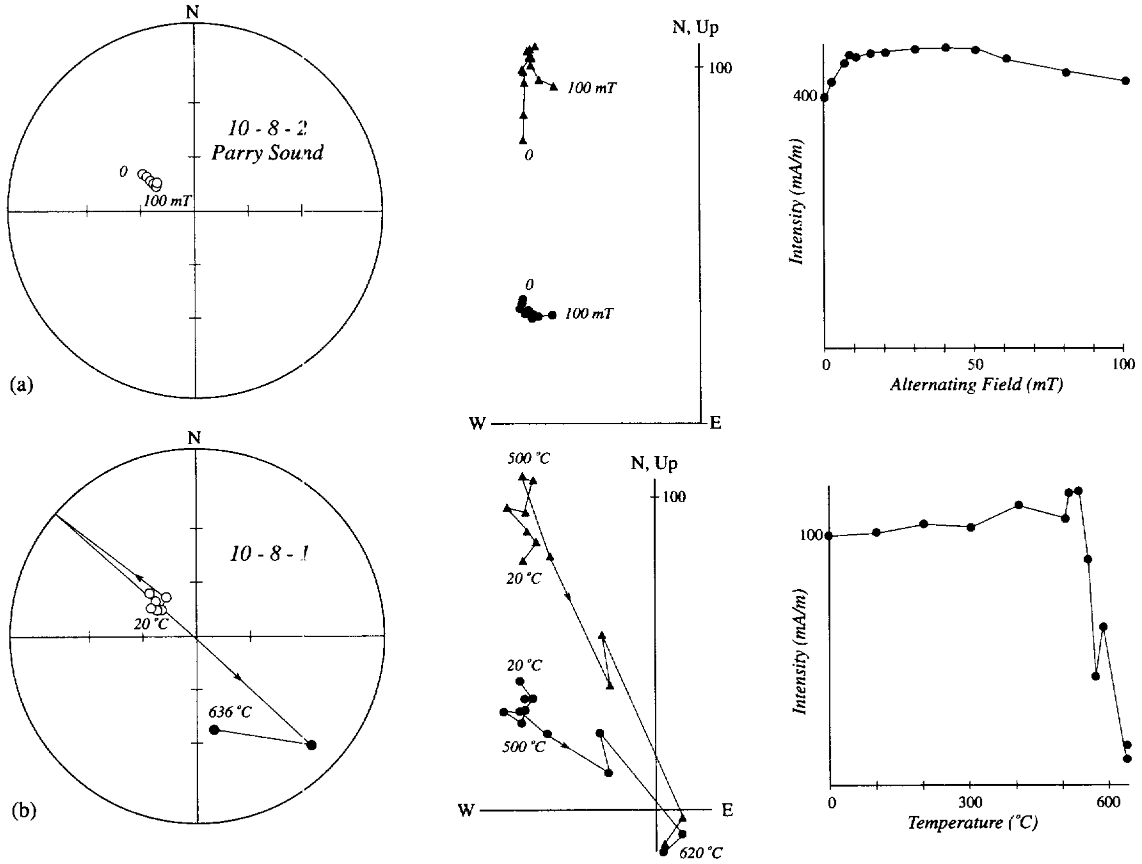

Fig. 6. AF and thermal demagnetization data for two specimens of sample 10-8 from site 10 (Parry Sound domain). A_R is very hard in this sample, with coercivities mainly >50 mT and unblocking temperatures between 500 and 620°C (single-domain magnetite + hematite). Projections and symbols as in Fig. 4.

The NRM of sample 10-8 is almost entirely A_R with a small present earth's field overprint (Fig. 6). A_R has 500 to >620°C unblocking temperatures and very high coercivities. Magnetite and hematite seem to carry about equal fractions of A_R in 10-8-1, while hematite dominates in 10-8-2.

These examples illustrate some general features in the behavior of our samples. A_N and A_R are easily separated from soft viscous overprints acquired in the present earth's field. The remanence carriers are magnetite of single-domain or pseudo-single-domain size, with coercivities typically from 10 to 100 mT and unblocking temperatures from ≈400 to 580°C, and single-domain hematite, with coercivities >100 mT and unblocking temperatures >600°C. When A_N and A_R coexist in the same sample, A_N usually overprints A_R (e.g. Figs. 4 and 5). If both are partial thermoremanent magnetizations (TRMs) carried by the same mineral, A_R must be slightly older than A_N. The A_R and A_N directions are so similar, however, that the age difference must be small.

7. Average paleomagnetic directions and poles

Average normal (A_N), reverse (A_R) and combined $A_N + A_R$ site mean paleomagnetic directions for 12 subdomains and zones are given in Table 1. Typical distributions of site mean results were shown in Fig. 2. The A_N and A_R subdomain averages are plotted in Fig. 7. A_N and A_R are almost exactly antipodal: there is no significant difference between R results (after their directions are reversed) and N results at site, subdomain or grand mean levels.

Table 1
Paleomagnetic mean directions by lithotectonic region

Region	D (°)	I (°)	α_{95} (°)	k	n
Normal polarity or A_N directions					
North of GF	50	+73	20	12	6
GFTZ	106	+76	13	18	8
Kiosk	90	+70	10	46	6
Britt	113	+72	18	49	3
Shawanaga	78	+74	10	143	3
Parry Sound	106	+60		21	2
Novar	120	+72		37	2
Huntsville	106	+61	32	16	3
McLintock	98	+53			1
Algonquin	138	+66	50	7	3
Muskoka	92	+70	28	21	3
Reversed polarity or A_R directions					
North of GF	266	−40			1
GFTZ	284	−57			1
Kiosk	282	−66	27	13	4
Britt	288	−39		17	2
Shawanaga	277	−70		8	2
Parry Sound	306	−67			1
Novar	291	−66		23	2
Huntsville	287	−49	25	25	3
McLintock	284	−53	15	25	4
Algonquin	308	−58	20	16	5
Rosseau	301	−73			1
Muskoka	268	−68	8	76	6
Normal + reversed (A_N + A_R) directions					
North of GF	61	+69	20	10	7
GFTZ	106	+74	12	19	9
Kiosk	275	−68	10	25	10
Britt	290	−59	22	14	5
Shawanaga	267	−73	15	27	5
Parry Sound	292	−62	22	33	3
Novar	295	−69	15	38	4
Huntsville	287	−55	15	21	6
McLintock	283	−53	18	19	5
Algonquin	311	−61	16	13	8
Rosseau	301	−73			1
Muskoka	269	−69	8	49	9

D and I are cleaned NRM declination and inclination, averaging n site mean data in a region; α_{95} and k are Fisher [35] statistics: radius of the circle of 95% confidence about the mean direction and precision parameter, respectively.

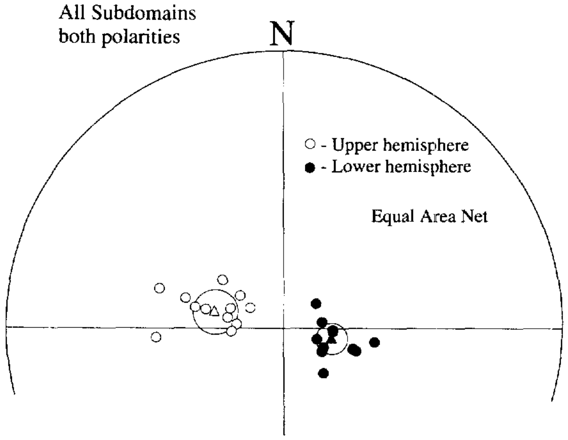

Fig. 7. Mean directions of cleaned A_R (open symbols) and A_N (closed symbols) magnetizations for 12 lithotectonic subdomains and regions. Triangles are the mean R polarity and N polarity directions, averaging all subdomain results. Circles indicate cones of 95% confidence about the means.

In the combined subdomain average results, α_{95} values range from 8 to 22° and the Fisher precision k is 10–49. The rather low precisions reflect between-site dispersion, due most probably to differences in average cooling times and/or TRM blocking temperature (T_B) ranges between widely separated sites. Most of the differences between subdomain mean directions in Fig. 7 are not significant, i.e. the circles of 95% confidence overlap, but there is an interesting distribution between higher and lower inclinations which appears as a trend in the corresponding paleopoles.

Paleomagnetic poles calculated from the combined $A_R + A_N$ subdomain results are listed in Table 2 and compared in Fig. 8 to the conventional Late Proterozoic Grenville Track of the Laurentian apparent

Table 2
Paleomagnetic poles corresponding to A_N + A_R mean directions (Table 1) for the various lithotectonic regions

Region	Latitude of pole (°S)	Longitude of pole (°E)	dp (°)	dm (°)
North of GF	49	155	29	34
GFTZ	29	134	20	22
Kiosk	29	147	14	17
Britt	14	149	25	33
Shawanaga	36	141	24	27
Parry Sound	15	145	27	34
Novar	20	137	22	26
Huntsville	12	154	15	21
McLintock	13	158	17	25
Algonquin	5	135	19	25
Rosseau	22	130		
Muskoka	33	147	11	13

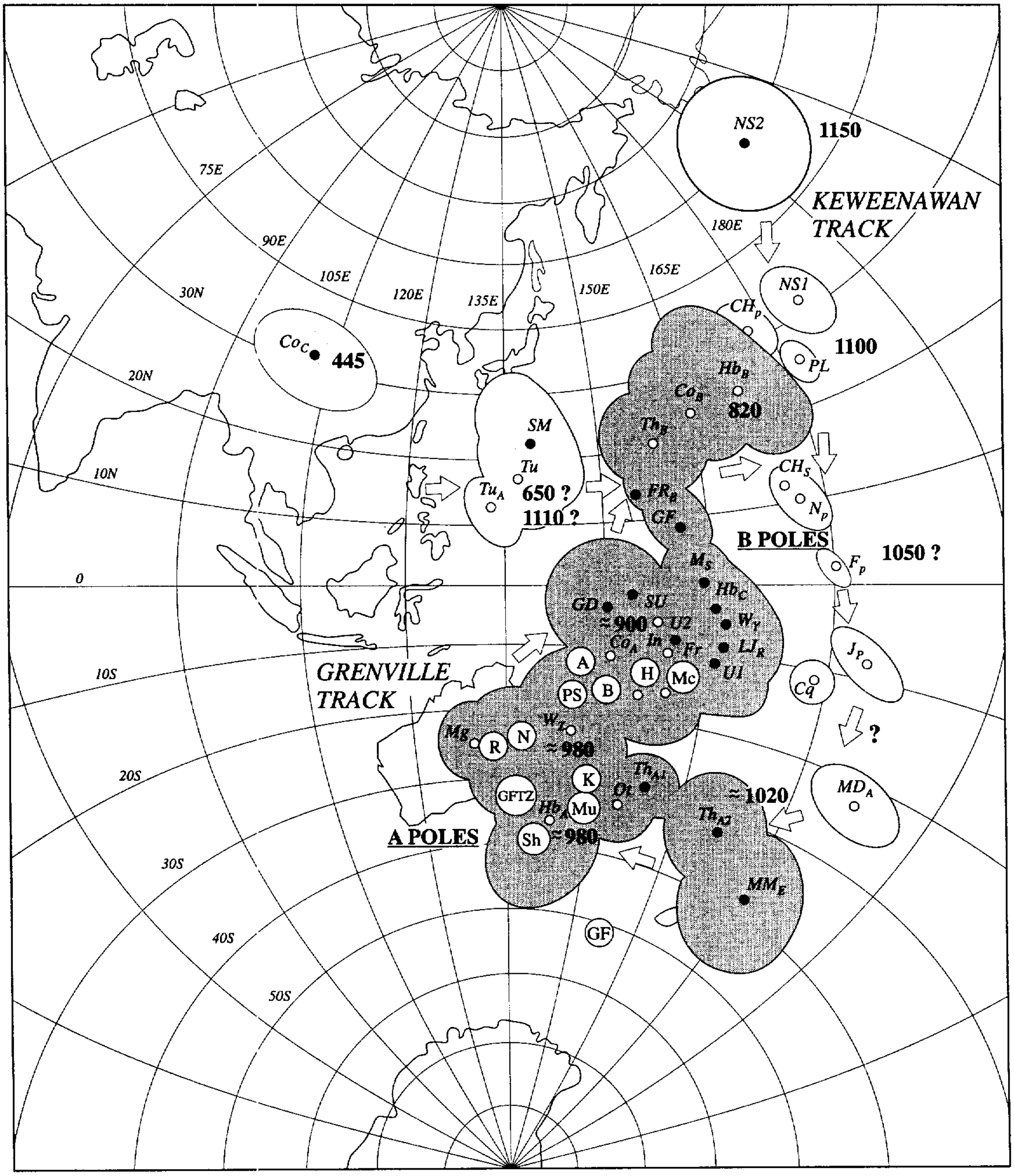

Fig. 8. The Grenville (~1020–820 Ma) Track of the Laurentian APWP (after Ref. [6], where the various paleopoles are identified) showing the distribution of $A_N + A_R$ paleopoles for the different lithotectonic regions of the CGB (abbreviations as in Fig. 1). There is a general northward trend of paleopoles with increasing distance of the corresponding region or subdomain from the GF, suggesting that regions near the GF were magnetized first (around 980 Ma) and more distant regions were uplifted, cooled and magnetized later (≈920 Ma for the youngest). B and Mu do not fit this pattern, however.

polar wander path (APWP). The time calibration of the Grenville Track is based on joint paleomagnetic and $^{40}Ar/^{39}Ar$ thermochronometric studies of two formations, the Haliburton intrusions of the Hastings area in the CMB [3,20] and the Whitestone anorthosite (WS in Fig. 1) of the Parry Sound domain in the CGB [21,25]. The ages of paleopoles corresponding to high-T_B and low-T_B partial TRMs were determined from $^{40}Ar/^{39}Ar$ plateau ages for hornblende and biotite by matching closure temperatures for Ar diffusion in these minerals to the measured T_B ranges of the partial TRMs. The paleopole ages of ≈980 Ma in Fig. 8 are tied to hornblende and the ≈900- and 820-Ma paleopole ages are based on biotite.

These two studies are definitive because they link $^{40}Ar/^{39}Ar$ and paleomagnetic data for individual formations or small regions. The $^{40}Ar/^{39}Ar$ data of Cosca et al. ([32]; see Fig. 1) proved less suitable for calibrating the APWP because we were unable to obtain stable paleomagnetic results at sites where hornblende and biotite results were available. There are also rather large differences between hornblende dates at nearby sites, e.g. 930 and 1005 Ma for sites ≈35 km apart in the Huntsville subdomain (Fig. 1). For these reasons, we were not able to make a site-by-site comparison between our paleomagnetic results and Cosca et al.'s $^{40}Ar/^{39}Ar$ data. Instead, we accept the standard time calibration of the Grenville Track, and date our mean paleopoles by comparison with these tie-point ages.

The age *range* we infer for the subdomain poles is ≈980–920 Ma (Fig. 8). By way of comparison, Cosca et al.'s *range* of hornblende dates (Fig. 1) is 1005–922 Ma. The age ranges are compatible, but the spatial trends in ages are different in the two data sets. The four more northerly hornblende dates average to (952 ± 18) Ma, while the five more southerly dates average to (978 ± 28) Ma. Thus there is a tendency for younging to the north. However, the standard errors overlap to the extent that the mean of one group lies within or very close to the error limits of the other group. Also, dates close to the maximum and minimum of the entire data set (930 and 1005 Ma) occur within ≈35 km of each other, in the same subdomain. A simple geographic progression in uplift ages is not strongly supported by these data.

The trend of subdomain poles along the APWP in Fig. 8, on the other hand, suggests younging to the south. Regions close to the Grenville Front (GF, GFTZ) have the most southerly (oldest) poles and subdomains farthest from the GF, such as Algonquin, Huntsville and McLintock, tend to have more northerly (younger) poles. There are some exceptions, e.g. Britt falls in the northerly group and Muskoka in the southerly group. The errors are large and the ovals of confidence in most cases overlap, but we should keep in mind that the same is true of the ovals of confidence for published paleopoles defining the Grenville Track itself (shown as dots in Fig. 8, with ovals in gray).

The paleopole and hornblende age trends can be reconciled if the Grenville Track actually youngs from north to south, as recently proposed by Weil et al. [36], principally to improve the match of APWPs from Laurentia, Baltica, São Francisco, Congo and Kalahari cratons in a Rodinia fit. D'Agrella-Filho et al. [37], in a similar fit of the same cratons, use the conventional Grenville Track, however. A 'reverse' Grenville Track has difficulty in explaining the 900-Ma WS biotite date and requires a further counterclockwise return loop to the north to accommodate the 820-Ma Haliburton pole.

To test the reality, or otherwise, of a possible progression in average magnetization age of subdomains, we plot paleopole latitude, a proxy for age of magnetization, versus distance from the Grenville Front in Fig. 9. The error bars on paleopole latitude (± dp, the semi-axis of the 95% confidence ellipse) are large enough that all regions could have a common magnetization age: a horizontal line at 23°S falls just within all the error bars. However, the error bars reflect cooling time differences caused by between-site differences in T_B ranges (e.g. 360–560 and 500→620°C for A_R in Figs. 5 and 6, respectively) as well as genuine errors in magnetic measurements. If we focus instead on the *average* pole latitude for each subdomain, there does appear to be a progressive change in paleopole latitude (and by implication average cooling age) of subdomains, from 35 to 40°S for regions at or near the GF to 10–15°S for southerly subdomains 165–195 km from the front. The Britt and Muskoka results do not fit the pattern, as mentioned before, and so any younging (or aging, in the case of a reverse Grenville Track) trend away from the GF is clearly only a first approximation.

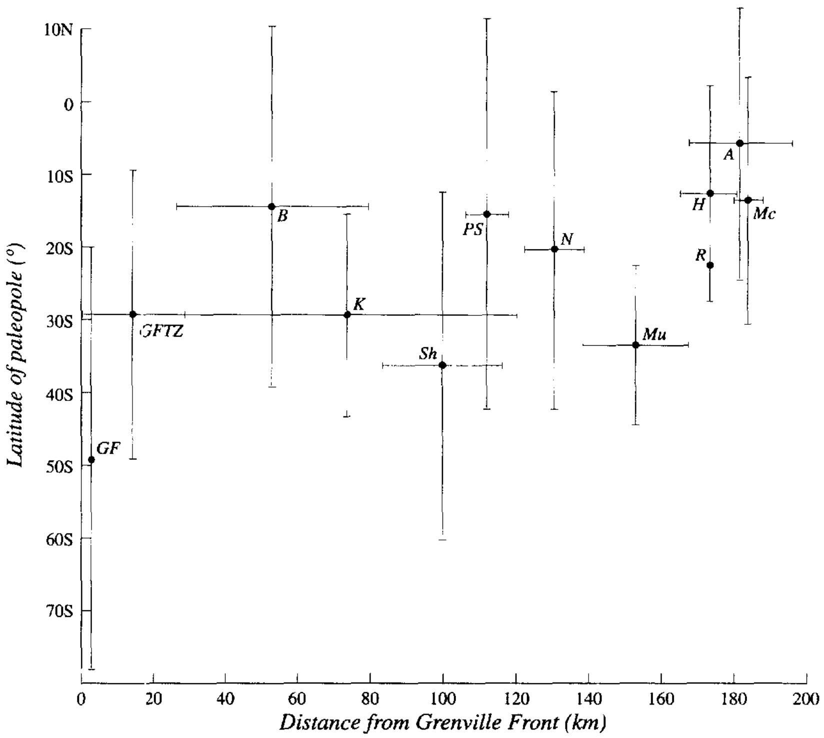

Fig. 9. A test of the general trend in Fig. 8 for terranes farther from the GF to have more northerly paleopole latitudes, i.e. younger magnetization ages. Error bars on paleopole latitude are determined from the ovals of 95% confidence about individual paleopoles.

8. Discussion

Our paleomagnetic estimates of average cooling ages of ≈920–980 Ma agree quite well with the range of published $^{40}Ar/^{39}Ar$ hornblende dates. Cosca et al.'s [32] dates for Parry Sound, Kiosk, Huntsville and McLintock (sub)domains range from 922 to 1005 Ma, with no particular spatial pattern; in fact, dates range from 930 to 1005 Ma, with analytical precisions of ±4 Ma, over short (≈35 km) distances within a single subdomain. Culshaw et al.'s [33] hornblende dates along the Georgian Bay coast for Britt and Shawanaga subdomains have precisions typically of ±5 Ma and are tightly grouped at 964–974 Ma, although they found significantly older ages of 1020–1067 Ma from Parry Island, a part of the Parry Sound domain which we did not sample in detail.

In the GFTZ, Culshaw et al. reported much older dates (1111–1417 Ma) with poorer analytical precisions. Smith et al. [34] also found anomalously old biotite and hornblende ages in the GFTZ. In both studies, the authors regard the GFTZ dates as unreliable because of excess Ar.

Our paleomagnetic poles, dated by comparison with the standard Grenville APWP, indicate that all the lithotectonic regions of the CGB were magnetized in a 60-Ma interval, from ≈980 to ≈920 Ma. There is some suggestion of a progressive trend in magnetization age, regions closer to the GF having been uplifted earlier and more distant regions later (Figs. 8 and 9). However, such a trend is not certain. Two of the CGB domains (Britt and Muskoka) do not fit the pattern. $^{40}Ar/^{39}Ar$ results from the CGB also do not support such a trend [32] (unless a reverse Grenville Track is used). The most trustworthy dates are hornblende plateau ages from domains beyond the reactivated zones flanking the GF. There are rather few of these, and although they agree with the range of magnetization ages, they show no obvious spatial pattern. $^{40}Ar/^{39}Ar$ results from the GF and GFTZ regions are anomalously high because of excess Ar. Previously published 'thermochron' maps of the Grenville, which show a strong gradient in ages away from the front, are probably misleading. The K/Ar dates on which the maps are based are spurious in the GFTZ and GF regions and it is these anomalously old dates that produce most of the apparent age trend.

Smith et al. [34] documented systematic trends in ^{40}Ar/^{39}Ar dates within the GF and GFTZ regions themselves. They found anomalously old dates, with a peak in apparent ages approximately 6 km south of the GF, which they attributed to a 'wave' of Ar associated with hydrothermal alteration during the Grenvillian orogeny. Because the ^{40}Ar/^{39}Ar data were disturbed throughout the region near the GF, it was not possible to date the hydrothermal activity directly.

In Fig. 10, we plot profiles of initial susceptibility and NRM intensity across the GF and throughout the GFTZ. Although there is a certain amount of dispersion at individual sites, the general pattern is similar to that seen in the ^{40}Ar/^{39}Ar data: a pulse-like or wave-like shape with a peak around 10 km south of the GF. The peak susceptibilities and NRMs (apart from two sites with anomalously high values that do not fit the overall pattern) are about two orders of magnitude higher than values at and just north of the GF and values >40 km south of the GF.

Another significant trend is that NRMs throughout the GF and GFTZ regions, whatever their magnitudes, have almost exclusively N polarities, whereas sites in domains beyond the GFTZ have about equal proportions of R and N polarities (Figs. 2 and 3). Both trends can be accounted for if the original NRMs of rocks near the GF were chemically overprinted by hydrothermal activity around 1000 Ma, the age indicated by the positions of the GF and GFTZ paleopoles on the Grenville APWP (Fig. 8).

The hydrothermal fluids responsible for remagnetization presumably circulated along fault systems south of the GF. Hyodo et al. [23] proposed a similar model to explain the irregularity of magnetic overprinting north of the GF. Many sets of faults have been mapped in the GFTZ, roughly paralleling the GF. Note, however, that the time of remagnetization is late compared to that of actual tectonic collision. Hydrothermal activity must have continued until ~1000 Ma, by which time the relict exotic terranes were already being uplifted as domains and subdomains of the CGB.

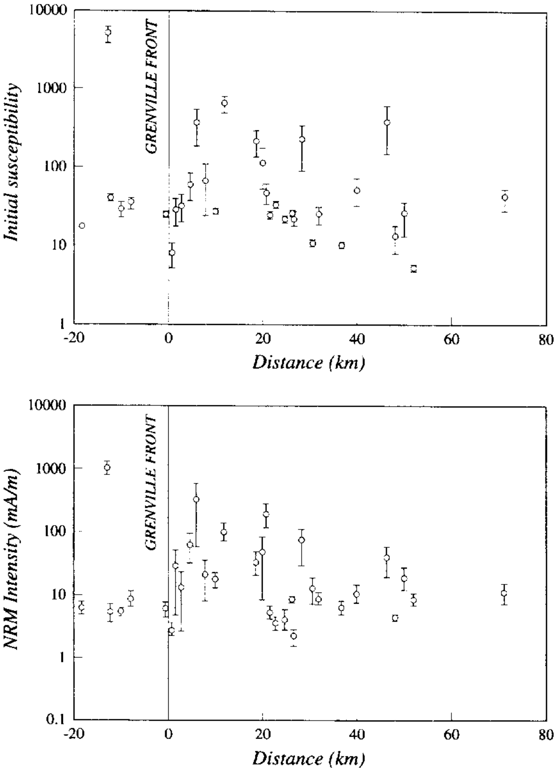

Fig. 10. Initial susceptibility and NRM intensity values as a function of distance from the GF. Error bars represent the range of values at each site. Both susceptibility and NRM values rise to a peak about 10 km south of the GF. Peak values are ≈100 times greater than values north of the front or at large distances south of the front. A similar wave-like pattern has been reported in anomalously old ^{40}Ar/^{39}Ar dates determined from the same region [34]. Both 'waves' or peaks are probably the result of hydrothermal alteration and remagnetization caused by tectonically driven fluid circulation along faults paralleling the GF.

These conclusions about the timing of tectonic events are based on paleomagnetic dating by reference to the Grenville APWP. The ^{40}Ar/^{39}Ar data in the GF region are too disturbed to date these events directly. However, U/Pb concordia data [18,19] support the hypothesis of tectonic activity followed by rapid uplift and cooling around 996–975 Ma.

9. Conclusions

NRMs found throughout the lithotectonic domains of the Central Gneiss Belt in Ontario are post-tectonic A NRMs similar to those in the Central Metasedimentary Belt. They originated as TRMs during uplift and slow cooling of these accreted terranes following their northwestward thrusting and stacking at depth. These NRMs have about equal proportions of normal and reversed polarities.

NRMs in reactivated regions of the Archean craton flanking the Grenville Front are also A magnetizations of similar age, but they were acquired rapidly as chemical remanences, probably as a result of hydrothermal circulation along faults paralleling the Grenville Front. These NRMs are almost entirely of normal polarity.

Paleomagnetic poles for the different domains, subdomains and regions studied fall along the 980–920-Ma part of the established Grenville Track for Laurentia. The range of magnetization ages matches the range of $^{40}Ar/^{39}Ar$ hornblende dates, although the geographic pattern of ages is not the same for the two data sets.

There is a possible spatial pattern in mean paleomagnetic poles of most CGB domains implying that regions closer to the Grenville Front were magnetized first and subdomains far from the front were uplifted through their blocking temperatures later. A similar, but more pronounced pattern was claimed previously on the basis of K/Ar thermochrons and paleomagnetic 'zone poles', but these patterns are suspect because they are biased by anomalously old K/Ar ages and chemical overprinting of NRM in the Grenville Front Tectonic Zone (GFTZ), which were unrecognized at the time.

NRM intensities and susceptibility values vary in a wave-like or pulse-like fashion in the GFTZ, reaching a pronounced peak ($\approx$100 times background values) about 10 km south of the Grenville Front. A parallel pattern has been recognized in anomalously high $^{40}Ar/^{39}Ar$ dates in the same region. Both peaks are likely due to a 'wave' of hydrothermal alteration and remagnetization, fluids having been driven away from the Grenville Front.

Since the A magnetization in the GFTZ has nearly the same direction as A magnetizations in domains far from the front, hydrothermal activity along fault systems south of the front must have continued until $\approx$1000 Ma, long after the collisional orogeny. The $^{40}Ar/^{39}Ar$ data in the GFTZ are too disturbed to date these events. The timing is deduced paleomagnetically, by reference to the Grenville APWP, and is in agreement with zircon and titanite U/Pb dating of the GFTZ.

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